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A Space-Fed Local Oscillator for Spaceborne Phased Arrays

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Deployable, spaceborne phased-array antennas require lightweight structures that are nonrigid and deform dynamically in orbit. These array deformations are described by a time- and amplitude-weighted sum of characteristic mechanical modes of the array structure. These mechanical deformations degrade the array's radiation performance by reducing the gain, increasing the sidelobes, and generating pointing errors. The effects of these mechanical deformations can be partially compensated for by a space-fed local oscillator. This space-fed local oscillator uses a radiator on the back of the array to transmit the local oscillator signal to pickup elements connected to the array elements. This technique also potentially lowers the array's weight, eases its mechanical deployment, and reduces the complexity of its design.

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I. INTRODUCTION

Future satellite applications require lightweight, deployable phased-array antennas. These antennas typically have a large number of elements to obtain the required system sensitivity; concepts that would use from 10,000 to 40,000 elements are common. Recent research and development efforts have focused on large space structures and active array modules. As these technologies mature and system applications evolve, other aspects of spaceborne array design need to be addressed. In particular, the array signal-processing architectures require development. When a large number of elements are used in the array, the efficiency of array element combining networks is reduced; in addition, the insertion phase of these networks becomes sensitive to thermal variations. One can avoid these difficulties by downconverting each signal to an IF frequency and combining at an IF rather than rf frequency. In this way, the array element combining networks have less loss and sensitivity to phase variations. The distribution of the local oscillator (LO) signal thus becomes an important aspect of the overall array design.

Large deployable phased arrays for space application also demand lightweight construction. However, these construction techniques do not result in an ideally rigid structure, but one that deforms dynamically in orbit. These deformations are dynamically produced both by natural causes such as thermal loading as well as by on-orbit attitude adjustments and station keeping. Such deformations are typically described by a time- and amplitude-weighted sum of characteristic mechanical modes of the array structure. The rates of deformation are relatively slow, with frequencies on the order of 1/10 Hz.

The array's deformations also distort the phase distribution, because the array elements are mechanically displaced from an ideal planar surface. This phase distortion, in turn, degrades the radiation patterns of the array: the antenna gain is reduced, the sidelobes are increased, and point-

ing errors are generated. The classical antenna tolerance theory[1] is based on random phase perturbations, a description that physically models the manufacturing precision of reflectors. However, the phase perturbations produced by mechanical-mode deformations are best described by deterministic structural modes rather than by random, statistical perturbations. Mechanical deformation thus degrades the array pattern performance differently than does random perturbation. A striking difference between the deterministic and random perturbations is the beam pointing errors that result from mechanical modes having odd symmetry;[2,3] such pointing errors are not predicted by the classical analysis based on random perturbations. A space-fed LO will be shown to be effective in reducing the effects of the mechanical deformations.

The space-fed LO concept has other advantages for space applications, specifically with regard to weight, prime power requirements, reliability, and complexity. The array's weight is reduced in two ways: (1) the compensation provided by the space-fed technique offsets the array's performance loss when very lightweight, nonrigid structures are used, and (2) the weight of conventional transmission-line LO distribution networks is eliminated. When the array has a large number of elements, the prime power needed to generate the LO signals can be significant; the space-fed distribution will be shown to consume less LO power than conventional transmission-line networks. In addition, the free-space path is inherently more reliable than transmission-line networks; the transmission-line distribution technique requires not only the complexity of the networks but also a large number of frequency multipliers. The absence of transmission-line networks also reduces the complexity of folding the array for deployment.

II. CONCEPT DESCRIPTION

The space-fed LO depicted in Fig. 1 uses a central radiator on the back of the array to transmit the LO signal to pickup elements connected to the array elements. The central radiator may be deployed from the spacecraft in a rigid manner and a variety of rf designs such as one recently published[4] may be used. The pickup elements may be connected either to an individual array element or a limited subarray. Because the pickup elements are not on the earth-facing side of the array, they are shielded from ground-based interference by the presence of the array.

Because of its geometry, the space-fed LO technique partially compensates for array deformations. This compensation is illustrated in Fig. 2. The ideal array surface is planar, as indicated by the dashed line in Fig. 2. The array is designed so that the phase shift inserted by the LO to an individual array element is equalized for the planar surface. For example, as the array surface deforms to a position indicated by the solid line, i.e., toward the LO radiator, the phase of the LO is advanced while the phase of the field radiated by the array element is retarded. Similarly, when the array surface is deformed away from the LO radiator, the LO phase is retarded and the phase of the field radiated by the array element is advanced. This phase compensation is partial rather than exact, because the LO radiator has a finite height and the LO frequency differs from the frequency used by the array. The effectiveness of the compensation will be demonstrated later.

The conventional transmission-line distribution system shown in Fig. 3 uses a network that connects the individual array elements to a common LO source. For reasons of efficiency, phase sensitivity, and deployment variations, this routing would be done at a low frequency; the low frequency provided by a reference oscillator would be divided to service the array elements, where it would be multiplied sufficiently to reach the desired LO frequency. Amplification would be provided to achieve the proper level to

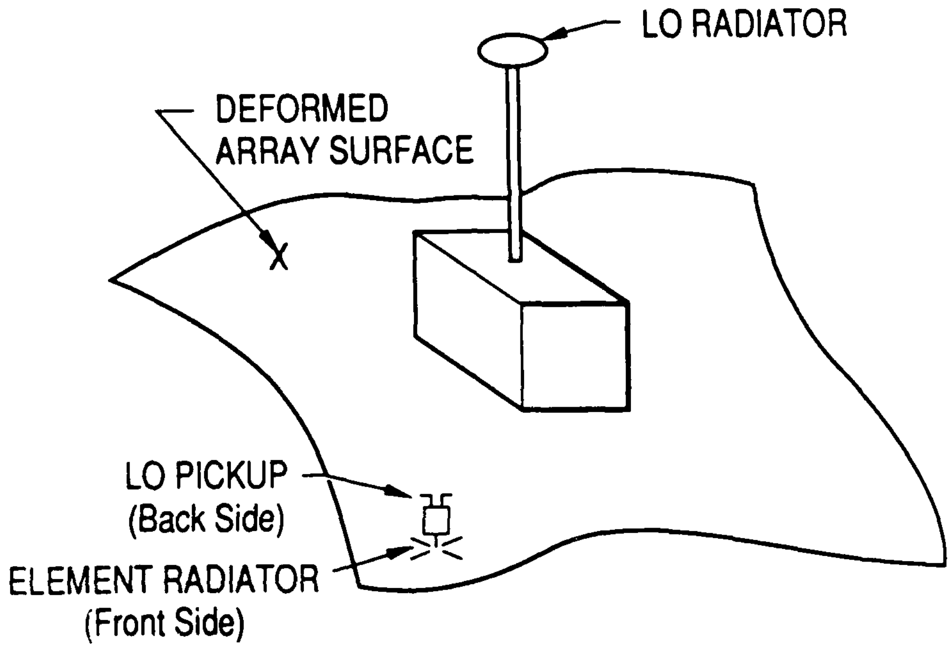


Fig. 1. Space-Fed Local Oscillator Concept

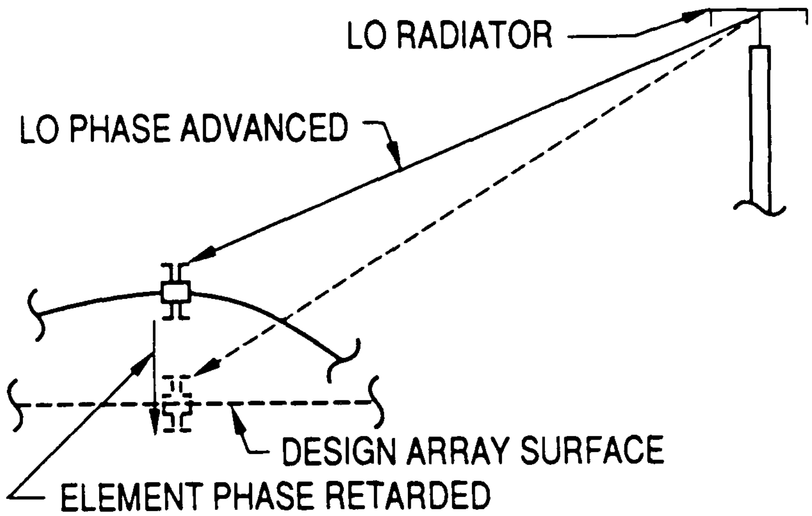


Fig. 2. Partial-Compensation Capability

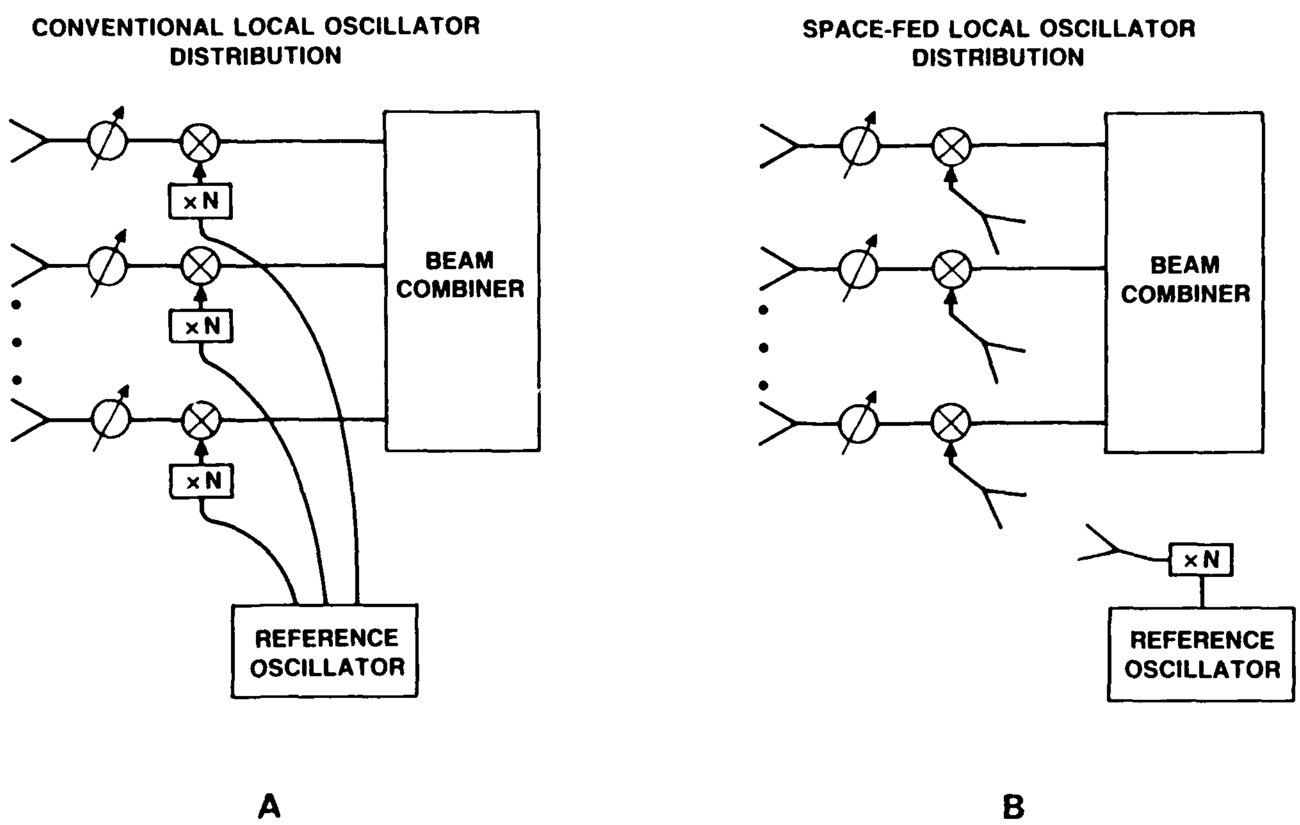


Fig. 3. Local-Oscillator Distribution Alternatives.
(a) Conventional Transmission Line. (b) Space-Fed Technique.

drive a mixer. The differences between the conventional and space-fed distribution systems are shown in Fig. 3. The design of the conventional LO distribution network requires system-specific information and a number of tradeoffs, e.g. the number of array elements, distribution network efficiency versus frequency, multiplier efficiency, gain partitioning for maximum power efficiency, as well as other constraints (such as the phase noise requirements after frequency multiplication).

The choice between space-fed and conventional LO distribution techniques depends on the specifics of the array design; however, some general comments can be made. Conventional distribution networks do not compensate for mechanical deformations of the array; thus, the space-fed distribution technique is appropriate for microwave applications that require good pattern fidelity. Prime power is important in space applications; one measure of the prime-power differences between the two distribution techniques is the requirement for LO power. Referring to Fig. 3, assume that both the conventional and space-fed techniques use the same gain values at the element to achieve the proper LO drive level for the mixer. The conventional technique suffers a reduction in the LO power as a result of (1) losses caused by the poor efficiency of the multipliers, (2) losses in the power division network, and (3) losses in the transmission line networks. In addition, because the multiplier in a space-fed system operates at a power level lower than that of its conventional counterparts, the efficiency of the multiplier for space-fed systems is less of an issue. For arrays having a large number of elements, the conventional distribution system consumes more LO power than the space-fed technique.

Design complexity is another issue: the conventional technique inherently has a large number of components, namely the frequency multipliers, the transmission line segments, and the divider circuitry. Reliability, particularly with regard to single-point failures, is very important in space applications. The space-fed radiator is a single element that demands high reliability; however, deployment techniques are well demonstrated, and redundancy can be provided in critical elements such as the

transmitting electronics. Unfortunately, with the conventional distribution technique, redundancy for the transmission lines is difficult to provide, and the requirements to make them lightweight may result in potential failures, particularly as the structure deforms in orbit. The potential weight differences have been previously described: the increase in the weight of the LO radiator and supporting boom in the space-fed concept is offset by the reduction in the weight of the distribution networks and by the weight reduction that occurs with the reduced stiffness requirements as a result of the deformation compensation. Finally, the presence of the transmission lines in the conventional technique further complicates the folding of the array surface required by deployment, making deployment difficult.

III. ARRAY PATTERN ANALYSIS

While Fig. 1 provides a conceptual picture of a typical spaceborne phased array, a variety of mechanical designs with differing stiffness and mechanical mode patterns will be encountered in practice. For example, the central area in Fig. 1 represents the main structure of the spacecraft, which would be more rigid than the portions of the array deployed from the central spacecraft structure. Rather than dwell on a specific design, we model the array mechanically as a uniform plate, whose mechanical modes are well known. This model illustrates the effects of deformation on the radiation pattern performance and the compensation provided by the space-fed oscillator. The time-varying deformation can be expressed as a weighted sum of the mechanical modes; however, because deformation varies slowly, the array can be considered as frozen in position at a given time. The corresponding degradation of the radiation pattern will be computed for an array surface having a fixed mechanical deformation.

The simplified mechanical model is also advantageous analytically, because the individual characteristic modes expressing the deformation are separable. Likewise, the array excitation of the elements is typically separable as well, since these array designs have a large number of closely spaced elements. Thus, the radiation patterns can be calculated from a line source rather than from a two-dimensional geometry. The generalization to a two-dimensional array is straightforward for both mechanical-mode functions and array excitations. The calculations will also be performed for individual mechanical modes, so that the sensitivity of the array patterns to particular mechanical modes can be observed. Furthermore, the calculation of the individual mechanical modes provides insight regarding the placement of mechanical control devices to maintain pattern fidelity for particular array applications.

Even with these simplifying assumptions, numerical integration is required to obtain far-field patterns. The patterns presented here are

based on a line source of length 2L, which represents the total width of the array. The LO radiator is located at a height H above the midpoint of the array plane. With these assumptions the pattern of the array is given by

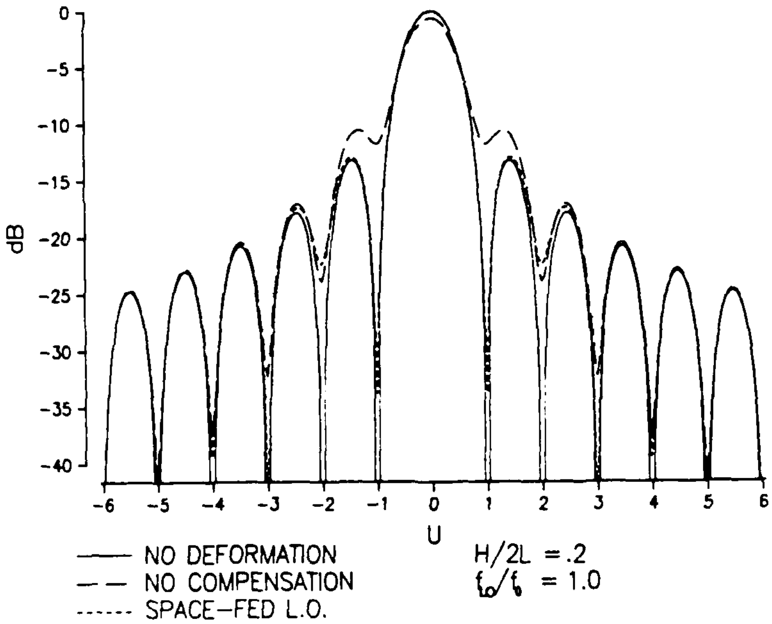
$$V(\theta) = \int_{-L}^{L} A(x) \exp[jk_0(\pm x\sin\theta + z(x) \cos\theta)]dx \tag{1}$$

where A(x) is the amplitude distribution of the array, k_0 is the free-space wave number, and x is the distance measured along the line source. The ± sign results from the ϕ directions, i.e., ϕ equals 0° and 180°. The phase contribution z(x) caused by the array element displacement d(x) is given by

$$z(x) = \begin{cases} 0 \text{ (no deformations)} \\ z(x) \text{ (conventional)} \\ z(x) \left[1 - \dfrac{f_{LO}/f_0}{\sqrt{1 + (x/H)^2}} \sec\theta\right] \text{ (space-fed)} \end{cases} \tag{2}$$

We obtained these equations for determining the radiation patterns by examining the insertion phase changes for both the LO signal and the field radiated by the individual array elements in their displaced position. The principal sensitivity of the phase changes results from element displacements normal to the beam direction. The radiated pattern is insensitive to small displacements in the array plane.

The computed patterns presented in Figs. 4 and 5 here show the patterns with no error (the ideal pattern), the patterns without compensation (the conventional LO distribution), and the patterns with the space-fed compensation. With space-fed compensation, f_{LO} is the LO frequency and f_0 is the rf frequency used by the array. The effect of the space-fed compensation is mathematically expressed by the term in brackets in Eq. (2). If the compensation were exact, this term would equal zero, and mechanical deformations would have no effect on array performance.



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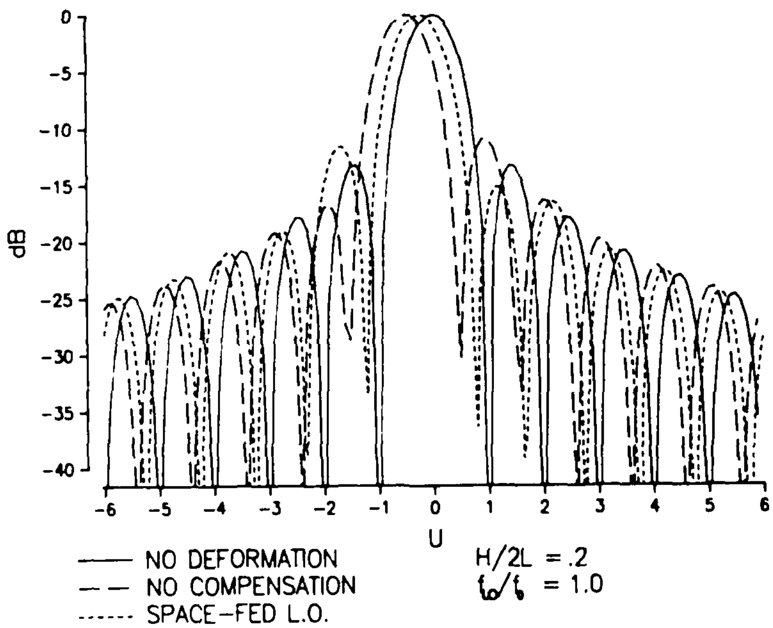

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Fig. 4. Array Patterns for First-Order Mechanical Mode and Uniform Amplitude Distribution. (a) Even Mechanical Mode with 0.2λ Peak Deformation. (b) Odd Mechanical Mode with 0.2λ Peak Deformation.

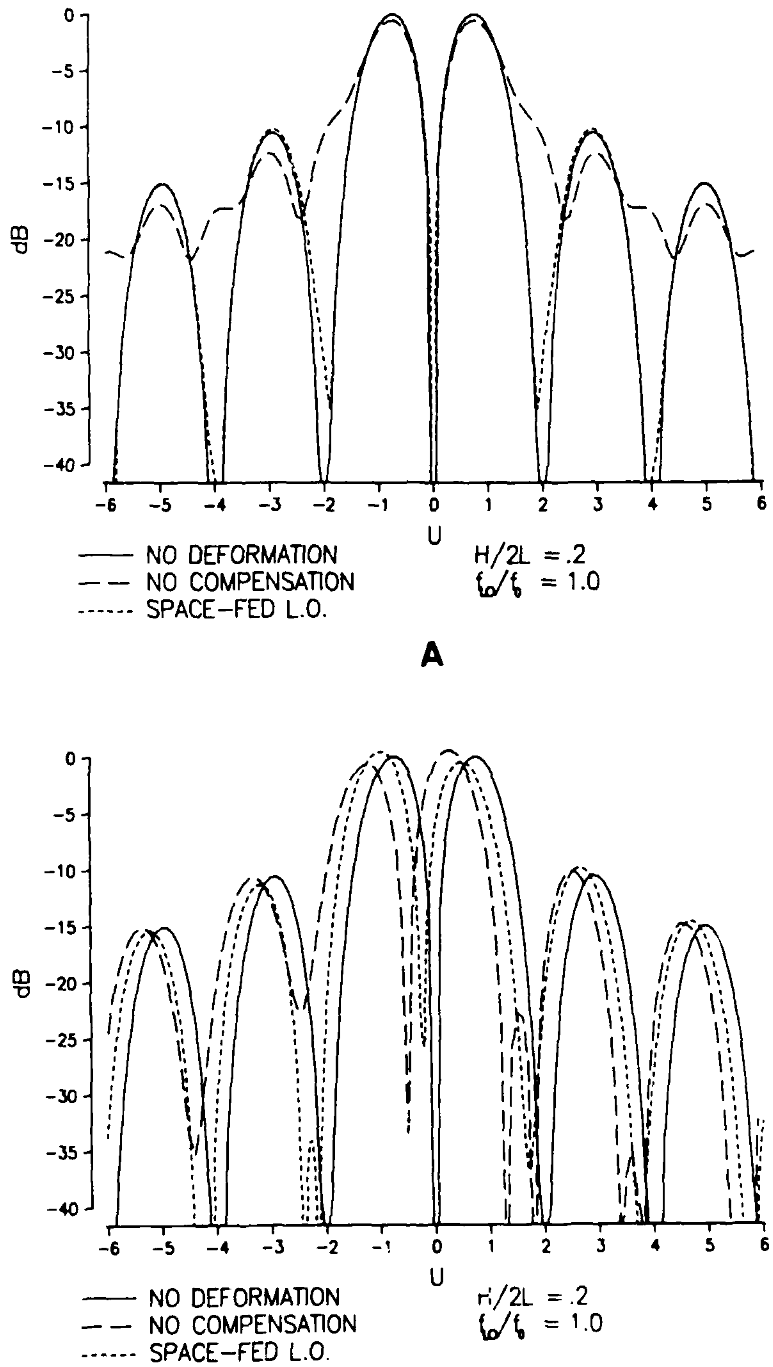

Fig. 5. Array Patterns for Difference Illumination for First-Order Mechanical Mode and Uniform Amplitude Distribution. (a) Even Mechanical Mode with 0.2λ Peak Deformation. (b) Odd Mechanical Mode with 0.2λ Peak Deformation.

The amplitude distribution used in these calculations is the ideal array excitation; however, practical arrays have some errors in the element excitations, which result from mutual coupling and amplitude and phase imbalances in the electronics and combining circuitry. Thus, the deployable phased arrays have two distinct tolerance problems, one caused by the mechanical deformations that are being addressed here and the second caused by the tolerances of the array excitation. The array excitation tolerances may be treated statistically[5] and incorporated in the overall analysis by being included in the array amplitude excitation, $A(x)$.

Example calculations can be performed for a wide range of parameters; however, arrays with uniform amplitude excitation are presented here to illustrate the effects of mechanical deformations and the compensation achieved by the space-fed LO technique. Further examples may be found in Refs. 2 and 3. The example patterns are plotted in terms of the usual normalized angular parameter u, where $\pi u = k_0 L \sin\theta$.

The patterns in Fig. 4 illustrate the effects of the first-order mechanical modes, where the peak deformation from the ideal array plane equals 0.2 wavelength. Both the even (cosine) and odd (sine) modes are presented in this figure. These patterns are shown for one particular instant of time, and vary in time with the mechanical oscillation. A quarter of a mechanical period later in time, the mechanical deformation is zero and the ideal pattern is achieved. By one-half of a mechanical period after the time used in Fig. 4, the patterns reverse where u equals 0. Since the even modes are symmetric, the degradation in the pattern is the same as that shown in Fig. 4(a). However, for the odd mechanical modes, the beam-pointing error caused by mechanical deformation is displaced opposite the axis where u equals 0. Thus, the time variation of the mechanical modes is particularly important for mechanical modes having odd symmetry; the beam-pointing error for these modes varies with time.

For the array with space-fed compensation, the height of the LO radiator above the array plane is one-fifth of the overall array length; for example, if the overall array length is 100 ft, the height of the LO

radiator above the array surface is 20 ft. While this is a relatively short height, practical designs would require deployable boom technology and reasonable stiffness. This short boom height was used in this example to illustrate that the space-fed technique provides partial compensation even with a short LO height. In addition, the LO frequency is assumed to be the same as the rf frequency used in the array design. This frequency ratio is approximately unity for microwave designs that are sensitive to mechanical deformations. As may be seen from Eq. (2), the compensation is not significantly sensitive to the difference between the LO frequency and the frequency used by the array.

Some systems require tracking capabilities from the antenna. A typical tracking implementation for an array is to divide the array into four subarrays, then use sum and difference combining of the subarrays in a monopulse fashion. In this case, the array generates a difference pattern for tracking purposes. In operation, the difference pattern null is aligned with the signal direction by means of feedback control techniques. The null of the difference pattern is designed to coincide with the boresight axis of the antenna. The effects of mechanical deformation on difference patterns are shown in Fig. 5. Again, the amplitude distribution on both halves of the difference pattern is uniform for these patterns; the peak mechanical deformation is 0.2 wavelength; and for the space-fed technique, the height of the LO radiator is one-fifth of the overall array width. The patterns in Fig. 5 also correspond to the lowest-order even and odd mechanical modes.

As illustrated by these examples, the effects of mechanical deformation on array performance are quite dramatic, even for the relatively small deformation amplitude. The even mechanical modes result in gain loss, an increase in the sidelobe levels, and filling of the nulls of the undeformed pattern. The odd mechanical modes result in less gain loss than do the even mechanical modes, in a sidelobe structure that is not symmetric, and, more important, in a significant pointing error that varies with time. The patterns in these examples clearly demonstrate the effectiveness of space-

fed compensation, particularly in the case of the even-mode deformation; however, while space-fed compensation reduces the pointing errors, some error remains. These examples illustrate the effects of the lowest-order mechanical modes; the pattern distortion caused by high-order mechanical modes occurs both far from and near to the main beam.

The pointing errors that result from odd mechanical modes are significantly important for many systems. The errors are time-varying, so that calibration techniques must incorporate the time variation of the mechanical motion. The pointing errors as a function of the peak deformation are presented in Fig. 6 to describe the sensitivity of the pointing errors. The errors for the boresight shift (in the case of the sum beam) and the difference pattern null location (in the case of the difference pattern) are shown. As a reference, for uniform illumination the half-power beamwidth corresponds to Δu equals 1. Pointing errors that are a significant fraction of a beamwidth can result from odd mechanical modes that have a relatively small amplitude. The pointing errors are linearly related to the amplitude of the deformation within the range of these calculations. The space-fed technique significantly reduces these pointing errors. The errors are further reduced by an increase in the height of the LO radiator above the array surface. For those applications that require good pointing performance, odd mechanical-mode excitation should be controlled, and a space-fed design with a relatively high LO radiator should be used.

The effects of the mechanical-mode deformations differ significantly from the effects of the random phase perturbations used in classical antenna tolerance theory.[1] However, the random phase error distribution differs physically from the phase perturbations generated by mechanical modes that follow a deterministic functional form. The pointing errors and asymmetric sidelobe distributions produced by odd mechanical modes are not predicted by the symmetric random phase perturbations. In classical antenna tolerance theory, the simple exponential function is widely used to estimate gain loss. The rms value for the lowest-order even mechanical mode was computed, and was found to be 0.3078 times the peak amplitude of the

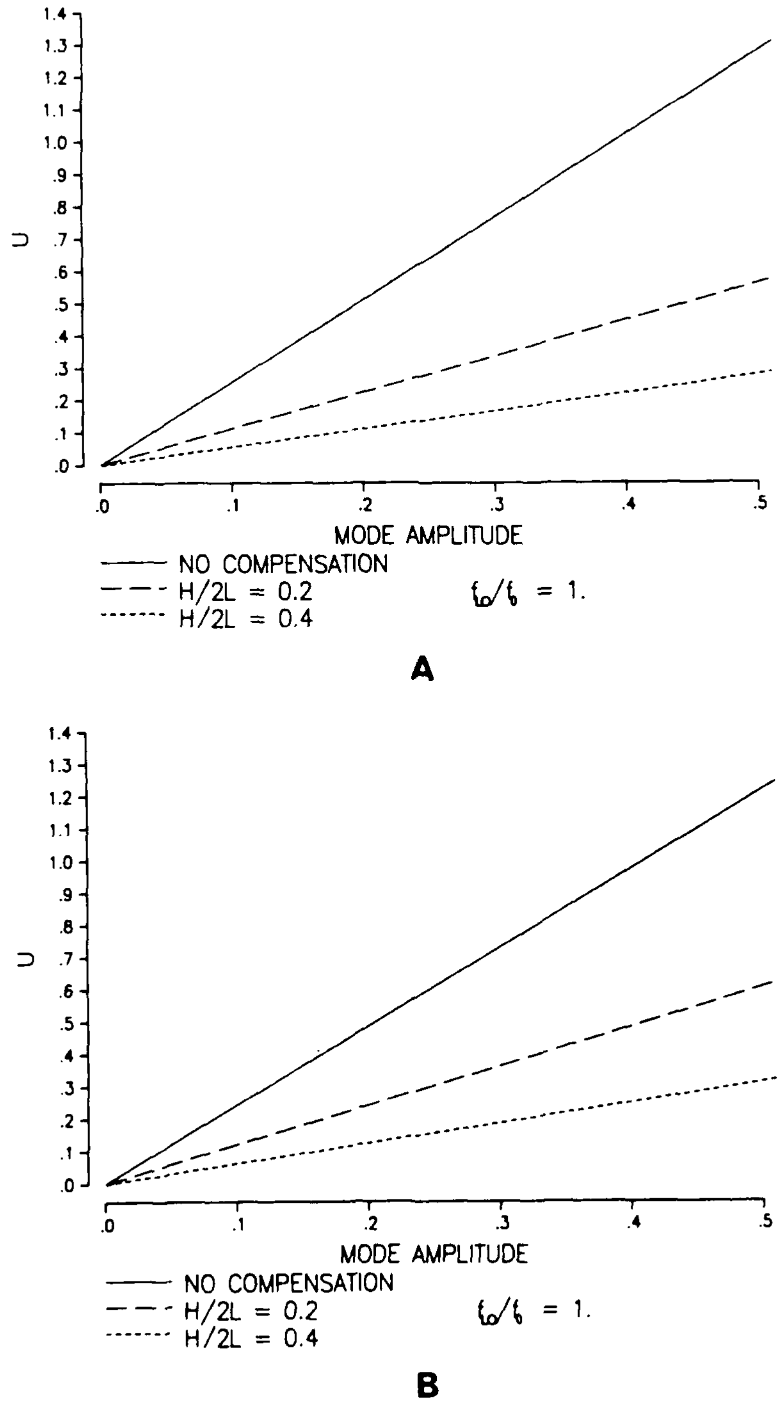

Fig. 6. Pointing Errors vs. Peak Deformation Amplitude for First-Order Odd Mechanical Mode and Uniform Amplitude Distribution. (a) Sum Beam. (b) Difference Beam.

deformation. For the example value of 0.2 wavelength used in Fig. 5, the exponential form of the classical tolerance loss equals -2.6 dB, which is significantly greater than the loss without compensation shown in Fig. 5(a).

IV. SUMMARY

Lightweight, deployable phased-array antennas will be needed for future space applications. Their lightweight construction results in a nonrigid structure that undergoes dynamic deformation in orbit. This deformation is described by the time- and amplitude-weighted sum of the characteristic mechanical modes of the structure. The effects of mechanical deformation on the rf performance of the array include gain loss, increases in the sidelobe structure, and pointing errors. A space-fed local oscillator (LO) technique is described that partially compensates for the effects of mechanical deformation. This technique also has potential benefits for space use, including reduced weight and complexity, power savings, and easier deployment. The effects of mechanical deformation differ from those of the random phase perturbation used in the classical antenna tolerance theory. For applications that require precision pointing, odd mechanical modes create time-varying pointing errors. Although the space-fed LO technique does not entirely eliminate these errors, it does reduce them.

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